January 2005 • NREL/SR-520-37347

Subcontractor Report

EFG Technology and Diagnostic R&D for Large-Scale PV Manufacturing

Annual Subcontract Report
1 July 2003–30 June 2004

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RWE Schott Solar, Inc.
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Operated for the U.S. Department of Energy
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1.0 Executive Summary:

This report contains an overview and a summary of the work performed between July 1, 2003 and June 30, 2004, in the second year of this contract. The work scope and the milestones and deliverables associated with some lower-tier subcontractors from Phase I (startup date March, 2002) were rescheduled for the second year of the subcontract on account of a delay in signing of the contract until April, 2003. Other tasks which did not involve external subcontractors were accelerated, including work on in-line diagnostics for wafer production, development of 12.5 cm EFG wafer growth and cutting, reflector module development, and tasks on automated computer aided data collection and analysis.

EFG ribbon manufacturing continued to expand in 2003-4, and now has reached over 40 MW of production. A variety of EFG wafer sizes is being produced: 10 cm x 10 cm, 10 cm x 15 cm and 12.5 cm x 12.5 cm areas. Cell production has also continued to expand, and a new 12 MW cell line was installed and brought on line in Billerica in 2003. Work is now in progress to optimize and improve cell performance, yield and throughput, with special emphasis on work to speed up wafer transfer which will allow the cell line to achieve up to 15 MW output. New module equipment also was installed and module manufacturing upgraded to 10 MW capacity, with plans to further increase this to balance cell and module production in 2005.

The main accomplishments for Phase II have been to complete feasibility studies on in-line diagnostic methods to monitor and control crystal growth parameters of EFG tube growth, develop photoluminescence monitoring of EFG bulk electronic quality, complete a second iteration of design for EFG furnaces to grow octagons with 12.5 cm faces and improve quality of wafers through reducing stress and raising mechanical yield in pilot manufacturing, develop new designs and evaluate critical performance aspects for a novel reflector module, and implement Computer Maintenance and Management Systems (CMMS) for Preventative Maintenance programs in EFG wafer manufacturing, and start to extend the system to our new cell line and to module manufacturing .

2.0 Program Scope

The objective of this subcontract over its duration is to carry our R&D to advance RWE Schott Solar Inc. (formerly ASE Americas) – "RSSI" - manufacturing technology, processes and capabilities of wafer, cell, and module manufacturing lines, which will help configure them for scaling up of EFG ribbon technology to the 50-100 MW PV factory level. The basic EFG technology principles have already been established and are being demonstrated on the scale of 10-20 MW manufacturing lines. By the successful completion of this effort, RSSI is planning to reduce overhead costs of production and of direct, variable manufacturing costs with the scale up of EFG processes and equipment currently in use. To achieve these objectives, RSSI needs to maintain or enhance yield, quality, process control, and throughput relative to present levels throughout the three areas of wafer, cell and module manufacture.

In the first year, RSSI initiated R&D to develop concepts for–and evaluate prototypes of–in-line diagnostic equipment in the following areas: monitoring and control of crystal growth temperature fields, crystal (tube) thickness, crystal flatness, crack detection in wafers, bond strength at interconnects, and electronic quality. RSSI evaluated improvements of its wafer technology by carrying out R&D on growth of large octagons of diameters ~38 cm, as compared to the present ~ 30 cm diameter octagon, and on laser cutting of the tubes. We also investigated automation of statistical process control (SPC) methods and Programmable Logic Controller (PLC) for process and equipment control. Computer Management and Maintenance Systems (CMMS) have been demonstrated and used in improving duty cycle and assisting in preventative maintenance functions. RSSI continued development of a prototype module using a reflector backing material. These results are described in our first annual report [1]

In Phase II, we continued development of in-line diagnostic methods (Task 5), advanced EFG technology in crystal growth and cutting of large octagon tubes with 12.5 cm faces (Task 6), reflector module (Task 7) and intelligent processing methods based on the CMMS platform for data collection and management on the factory floor (Task 8).

We made two oral presentations at the 29th IEEE PV Specialists conference, May 14-21, 2003, in New Orleans, summarizing the work done in our program, and these have been published in the Proceedings volume of the conference [2]. An oral program review of Phase II accomplishments was given at NREL on May 28, 2004.

The work scope and work in progress in individual tasks for Phase II are described below.

2.1 Task 5 In-Line Diagnostics

The PV technology for expansion of RSSI's manufacturing facilities is based on production of multicrystalline silicon wafers by the Edge-defined Film-fed Growth (EFG) technique. This task addresses the development and evaluation of diagnostic needs and equipment for monitoring of the manufacturing line processes and product quality. A survey of the requirements on diagnostic equipment and on available equipment was completed in Phase I. In Phase II, we have evaluated the most promising methods and completed optimization of methods for monitoring and controlling critical process steps in the wafer and cell manufacturing areas. (The module manufacturing area will be looked at in Phase III.) The status at the end of Phase II of these methods developed under this program are listed in Table 1 below.

Monitoring of manufacturing processes and product quality at RSSI has historically been carried out manually and with off-line methods. As equipment throughput increases and demands are made to reduce labor costs, it becomes necessary to implement in-line, automated methods–*as much as is practical*–to monitor manufacturing processes and guide improvements. In our vertically integrated manufacturing facility, we are concerned here with diagnostic tools which span all areas from silicon preparation through module production. Requirements for on-line diagnostic techniques vary depending on the process step and the type of information that is required. Although, in principle, it would be ideal to sample each and every part with a given diagnostic approach, this is not possible in an actual manufacturing setting. We have studied, therefore, a variety of statistical sampling techniques for several of the monitored parameters. In general, there are several levels of diagnostics and controls available, ranging from operator-intensive manual operations to highly automated computer-aided measurements. The following sections discuss the progress made in the manufacturing area.

Wafer production. Since several expansions have already been completed in the EFG crystal growth and laser cutting (wafer production) areas, the diagnostics development is the most mature there. CMMS was the first to be installed and demonstrated in crystal growth and laser cutting, and automated data collection is possible (see Task 8). Process control software has been installed on crystal growth furnaces for monitoring certain growth variables, e.g., for measuring on a continuous basis parameters such as temperature and buckle/amplitude. A method suitable for measuring thickness on-line during tube growth simultaneously on all faces of the octagon has been demonstrated, and equipment will be purchased and installed for optimization and integration into control algorithms.

In the laser cutting area, a crack detection method using an IR camera was evaluated, but shown to lead to a high frequency of false hits, particularly for cracks below 1 cm in length which are of the most relevance in yield. This method will be explored further in a manual mode as an R&D tool, and we will examine if it is cost effective to develop software to improve reliability and consistency of the method to automate it.

Table 1. Diagnostic requirements for manufacturing and status of evaluation of options as of the end of Phase II.

Area	Diagnostic approach(es)	Targeted procedure	Status
Wafers			
EFG furnace - die temperature	Remote pyrometer sensor	Continuous/automated	Completed/installed
Tube thickness	IR sensor	Continuous/automated	Feasibility completed.
Tube flatness	Capacitance sensor	Automated – in-situ growth measurement	Completed/installed
Crack detection (both after laser cutting and at interconnect)	Acoustic or laser sensor	Automated	Manual IR sensor method identified
Wafer Strength	Fracture twist test	statistical/daily	Completed
Cells			
Bulk resistivity	Four point probe	automated sampling	manual sampling
Bulk quality	PL or μ-PCD	PL/statistical- daily	Calibration in progress
Modules			
IC bond strength	Pull test	statistical/daily	Completed
Glass	Defect inspection	Manual	TBD- Phase III
Lamination	Process control of temperature/pressure	PC based	TBD-Phase III
Wiring	Continuity	Manual inspection	TBD- Phase III

Cell Line Diagnostics: Requirements on diagnostics are being upgraded to aid in enhancing throughput by improving and optimizing process steps in a new 12 MW cell line, which was installed at RSSI's facilities in Billerica in 2003. New module equipment is being evaluated and will be installed and operational during 2004. Work scope in this task in Years 2 and 3 is to carry out R&D to update in-line diagnostics for the new manufacturing equipment. Some diagnostic methods for these areas were developed in Phase II as summarized in Table 1 above.

General requirements for process and quality monitoring may be better understood from consideration of wafer transfer times in various steps in the manufacturing line. A good example may be found in the automated cell line which is just being installed in Billerica. This new line will be the focus of part of our diagnostic technique development programs in the Task 5 continuation on diagnostics in Phase III (Task 9). The cell processing line includes all steps from diffusion through cell testing (through which a given wafer can run continuously in principle, but which has various buffer locations in practice, in order to provide storage for partially processed wafers in case of individual process step equipment down-time). In order to put the capacities and cycle times in question into perspective, a general graph of capacity vs. cycle time (average transfer time per wafer) in a cell line, for different area wafers, is shown in Figure 1 below.

The diamond and square in Fig. 1 indicate current state-of-the-art technology being practiced at RWE Schott Solar. The new 12 MW cell line currently being optimized for throughput yield and efficiency under this program in Billerica was installed in 2003. A photograph of the cell line is shown in Fig. 2. This line is configured for transfer times represented by the square in Fig. 1, at about 3.2 s per wafer, which was upgraded from the capacity of the latest line (diamond at 3.6 s per wafer) developed at our other company facility in Germany in 2002 and 2003. The goal of the new Subtask 9.4 in the Phase III program will be to work on upgrading the process step equipment to reach first 2.7 (arrow) and then 2.3 s per wafer transfer times, and a nominal capacity close to 20 MW.

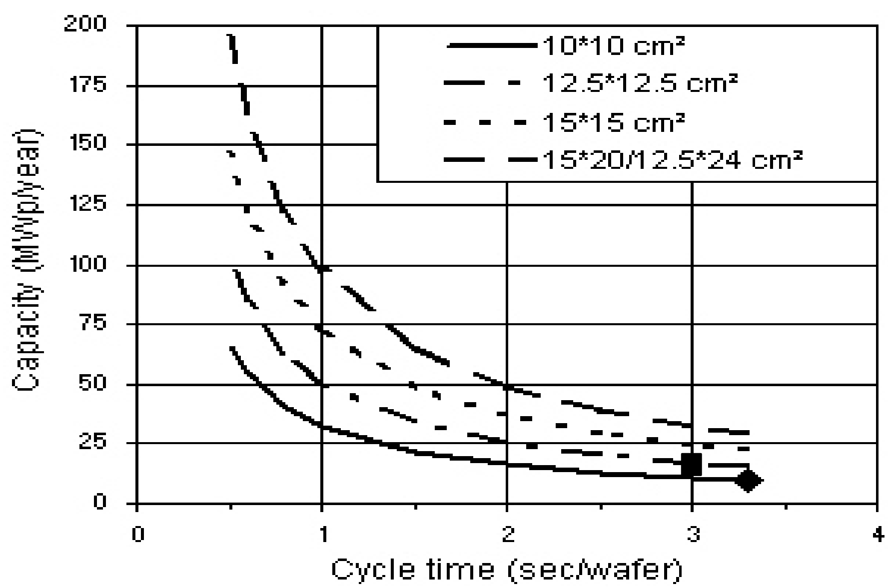


Figure 1. Relationships among cell line capacity, wafer cycle time and wafer area [from Ref. 2].

Future cell line technology which uses 12.5 cm x 12.5 cm wafers along with the improved transfer time of 2.3 s will be capable of running at over a 20 MW capacity with little change in basic equipment design. This is illustrated in Table 2:

Long range plans at RWE Schott Solar call for cycle times to be reduced to the order of 1-1.5 seconds for 12.5 cm x 12.5 cm wafers, to achieve single line capacities exceeding 40 MW on equipment currently rated at 12 MW.

Table 2. Capacity parameters for possible cell line upgrades for RWE Schott Solar cell line technology.

Cell Technology	Tack time (s)	Parts per hour*	MW capacity
Baseline 2002	3.6	1000	11.7 MW
New Billerica line	3.0	1200	14 MW
Goal Phase III	2.7	1325	16 MW
Goal 2005	2.3	1600	24 MW*
Goal long term	1.2	3200	45 MW*

* These last two capacity figures assume introduction of a 12.5 cm x 12.5 cm wafer.

The specifications which set the wafer transfer/cycle times for the processing equipment simultaneously set the same cycle time requirements for any diagnostic tools which are to be used on-line. Approaches found to be incapable of meeting the cycle times will be relegated for use as statistical sampling tools only.

Figure 2. New cell line at RWE Schott Solar in Billerica.

At the conclusion of Phase II work, we determined that we have to expand our original list of diagnostic requirements for the new cell line and have compiled the list in Table 3 for future study in Phase III. In Phase II, we replaced our four-point probe with a newer model and provided a data entry terminal, which both calculates the averages and stores the information into a database for later retrieval and trend analysis. Other key cell processing data in the table are routinely entered into a database for QC lots processed on every shift which are used to monitor line performance. Also, we have procured and installed a spectroradiometer for analyzing our cell test spectrum. Reliable procedures have been established which provide rapid assessment of our lamp spectra. The spectrophotometer is being used to help diagnose equipment problems with our cell testers with extremely rapid response time, and has led to improved quality and accuracy of our reported data.

To summarize, this task has demonstrated prototype equipment for in-line temperature field monitoring; control algorithms for crystal growth and EFG tube thickness and flatness measurement; in in-line equipment for detecting cracks in wafers and cells and statistical methods to use in the application of wafer fracture strength testing. Methods for bulk electronic quality measurements using PL, resistivity sampling after diffusion, and bond pull strength testing for interconnect evaluation have also been implemented. In Phase III, the focus will be on calibrating and applying these and other techniques for cell line yield and quality optimization and for throughput enhancement.

Table 3. Diagnostic requirements for new cell and module fabrication lines for Phase III R&D.

Area	Diagnostic approach(es)	Present procedure	Targeted procedure
Diffused junction: - sheet resistivity - P-dopant profile - Dopant film - Furnace temps	Four-point probe	Manual sampling	Automated sampling
Glass Etch: - Dopant film removal - Lack of residue	Hydrophobicity assessment, visual check	Manual sampling	Manual sampling, *plus* surface analyses to assess process changes
Silicon Nitride antireflection coating: - Thickness and η_R - Wafer temperatures - chamber gases	Ellipsometer	Minutes/manual	seconds/manual
Metalization – Back - Pattern alignment - Solder dot resistance - Surface recombination	*described at right*	visual check using templates/sampling	vision system/all cells
Metalization - Front - Busbar width - Finger shadowing - cosmetic inspection	*described at right*	Microscope check/sampling	vision system/all cells
Lifetime	PL – see Table 1	See Table 1	See Table 1

2.2 Task 6. EFG Manufacturing Technology Scale-Up

Crystal Growth. We continued the development of the 12.5 cm growth furnace and the laser cutting station in Phase II of this program. There was a specific focus to apply improved in-line diagnostics to raise 12.5 cm wafer quality, both with respect to mechanical and electronic characteristics, with the goal of reaching par with our current production 10 cm octagon growth systems. One aspect of this work has involved developing sensors which will improve furnace temperature control and which track wafer flatness during growth, as discussed in Task 5 above, which will be continued in Task 9. Another aspect was support work for improving hot zone designs and shortening the engineering steps and time required to develop new crystal growth concepts, which was carried out with the help of lower-tier, university subcontracts. Magnetic field and thermal models of the EFG large diameter system hot zone have been developed and applied to engineering design by Stony Brook University, and stress analysis of the growing tube in order to improve material properties of wafers has been initiated at Harvard University.

In Phase I of our program, EFG furnace development work focused on improving the design of a prototype unit for production of 12.5 cm x 12.5 cm wafers. A prototype furnace design was recommended for production at the end of Phase I. Octagon tubes with 12.5 cm faces are now being routinely grown in a manufacturing setting to lengths of 4.6 m (180 in), with average growth speeds of 1.5 cm/min (0.6 in/min). While production EFG furnaces were being constructed, installed and optimized, concurrent R&D work in Phase II of this program focused on further improvement of wafer properties, particularly in areas of better thickness uniformity and reduced residual stress. As a result of improvements, the average thickness of 12.5 cm x 12.5 cm EFG wafers produced in manufacturing has now been reduced from 350 microns at the start of the program to 300 microns while maintaining yields acceptable in large scale manufacturing.

The major challenges for R&D work in this task in Phase III are to continue to improve on the thickness uniformity and the flatness of the wafers. Thickness uniformity has become a central problem, as has stress. Both factors stand in the way of expanding to larger EFG tube diameters and wider face dimensions with reduced thicknesses of EFG wafers. The source of these uniformity, flatness, and stress issues primarily arises from thermal asymmetries around the perimeter of the tube, which makes the range of thickest to thinnest wafers produced marginally acceptable for cell manufacture. In the current design of the 12.5 cm furnace, we have determined that we have reached the limit of uniformity which can be achieved with adjustments in a single main heating coil. These limits also apply to plans for a 15 cm face-width octagon furnace, which would be based on the same 12.5 cm face technology. The larger face octagon thus would not be capable of performing at yield and throughput levels that are cost effective unless these problems are resolved.

As a consequence, the work scope in this task in the original proposal has been modified for Phase III. The proposed work to extend EFG technology to produce 15 cm x 15 cm wafers from larger multi-sided EFG polygons of the present furnace design has been halted in Billerica, and a redesign of the EFG furnace has been started in another company location. As a result, work to increase the diameter of the current EFG furnace will be discontinued under this program. Resources from Task 9 will be transferred to Task 11 on new cell line optimization in Phase III, in subtask 9.4, as outlined above.

The marginal thickness uniformity in the present furnace design looms as a critical near-term issue that carries over to our effort to achieve the program target thicknesses of 250 microns in the 12.5 cm EFG furnace. While stress limitations to growth lead also to unacceptable non-flat or buckled ribbon as thickness decreases, it can be overcome to a great extent by slowing down the growth speed and sacrificing productivity in the short term, while solutions to stress reduction are developed. The issue of thickness uniformity directs our work scope for Phase III of our program toward reduction of factors affecting thermal balance in the hot zone. Among the strategies we will examine is on-line thickness measurement diagnostics to evaluate causes of thickness nonuniformity(Table 1), and provide a means to establish feedback loops for *in situ* growth modifications, improved mechanical alignments of furnace hot zone components, and dynamic modifications of heat transfer/isotherms during growth during transient phases of growth.

Laser Cutting Technology R&D. Cost reductions in laser cutting are primarily limited by labor. We have explored more effective utilization of lasers, evaluated high speed lasers, and studied the concept of cutting simultaneously on opposite sides of the tube with two lasers in this program. A higher speed laser has been introduced and thoroughly tested in production in Phase II of our program. This laser can cut up to 1.6 in/s as compared to 1 in /s of the current production laser. With a higher duty cycle due to a more robust design and use of fiber optics cables in place of mirrors for beam delivery, this laser has been demonstrated to lead to a 20+ % increase in capacity of a laser station, with commensurate 20% decrease in labor costs.

We have developed a design and written specifications for a new laser station in this task which could employ two lasers to double wafer production rates per station. The economics of retrofitting our production lasers is not favorable at this time, although this design strategy will be useful for future EFG wafer factory expansions.

Other improvements in laser technology have come with the help of applying diagnostic methods for testing of wafer strength (Table 1) and improved information collecting networks (Task 8). The four point twist test described in a previous report is valuable in identifying deficiencies in laser focusing and equipment malfunctions, such as in wafer backpad alignment, and etch effectiveness. This method is now routinely used in the manufacturing line for wafer mechanical strength monitoring.

2.3 Task 7. Reflector Module

This task involves the continued development of a reflector module design demonstrated and patented on a previous DOE/NREL subcontract [1]. In the reflector module, a light-reflecting film is placed behind the cells, which concentrates incident light falling in intentionally large spaces left between cells, back onto the cells (Figs. 3 and 4). The cost gain from the light enhancing film is that it allows for a reduction in the number of cells from a standard terrestrial module while still maintaining the power output from a module of equal area. This task is expected to result in a module configuration incorporating a reflector backing material with EFG cells with a target to reduce the cell requirements by 25% while maintaining module output power. Additionally, this Task is expected to result in a manufacturing strategy, data on encapsulant evaluations and recommendations, and floor layout for production of the reflector module. In Phase I, RSSI carried out investigations on reducing module costs by completing a design and fabrication of a number of prototypes of a reflector module with a novel backskin material.

The main accomplishments in Phase II for this portion of the work effort include: 1) module design was scaled up to a 300 W size in Phase II and a number of modules up to 50 W sizes were made for outdoor performance verification and for environmental testing in both outdoor exposure and in accelerated temperature/humidity cycling; 2) stress analysis of various laminate material combinations were carried out to evaluate safety factors in design and determine stress-related causes of module failure in reliability testing.

Prototype reflector modules have been manufactured and provided to NREL for performance verification. Two modules, one measuring 1 foot by 1 foot (SN 03-0204), and the other measuring 22.25”x31.34” (SN 04-0204) were tested both at RSSI and at NREL. The latter is close to the area of our standard 50 W module. Test results for these prototype reflector modules are given below:

Outdoor testing. The open circuit voltage and short circuit current of the sample SN 02-0204 were measured outdoors using a multimeter, and then compared for the non-reflector and for the reflector cases. The results are summarized in the following table. A single cell coupon previously measured in the cell tester was used as a control.

Table 4. Outdoor test results for small area reflector

			Corrected values
Sample:03-0204	***Isc (A)***	***Voc (V)***	***Isc (A)***
w/o reflector	1.54	3.52	***1.38***
w reflector	2.34	3.564	***2.10***
Increment (%)	***51.95***	***1.25***	**51.95**

** Polyester was used as a insulator between the cells and the reflector backskin*

Indoor flash test. The electric characteristics of the sample SN 04-0204 were tested using the indoor flash testing machine. The same as the previous sample the non-reflector and reflector case were used. A 50-W calibration module was used as a control. The results obtained are shown below.

Table 5. Indoor flash test results for larger area reflector module.

Sample:04-0204	**Pp (W)**	**Ip (A)**	**Isc (A)**	**Voc (V)**	**Vp (V)**	**FF**
w/o reflector	25.42	1.45	1.61	21.62	17.53	0.73
w reflector	37.01	2.12	2.40	21.99	17.43	0.70
Increment (%)	45.60	46.35	48.84	1.68	-0.58	-3.85

** Polyester was used as a insulator between the cells and the reflector backskin*

Reliability problems were first seen in larger modules with the construct of a single glass and backskin shown in Fig. 4 made with a combination of RSSI’S proprietary encapsulant and the backskin. A stress analysis was undertaken to determine stresses arising in the laminate which could affect module reliability, and it was determined that the chosen materials produced stresses which likely would lead to delamination of the kind seen in the environmental tests. Through a lower-tier subcontract with Harvard University, we have completed stress analysis of the construction shown in Fig. 4 below, and find that significant glass/encapsulant interface stresses arise as a result of thermal expansion mismatch between the backskin and the glass. The tensile interface stress generally may be compensated by compressive stress imposed

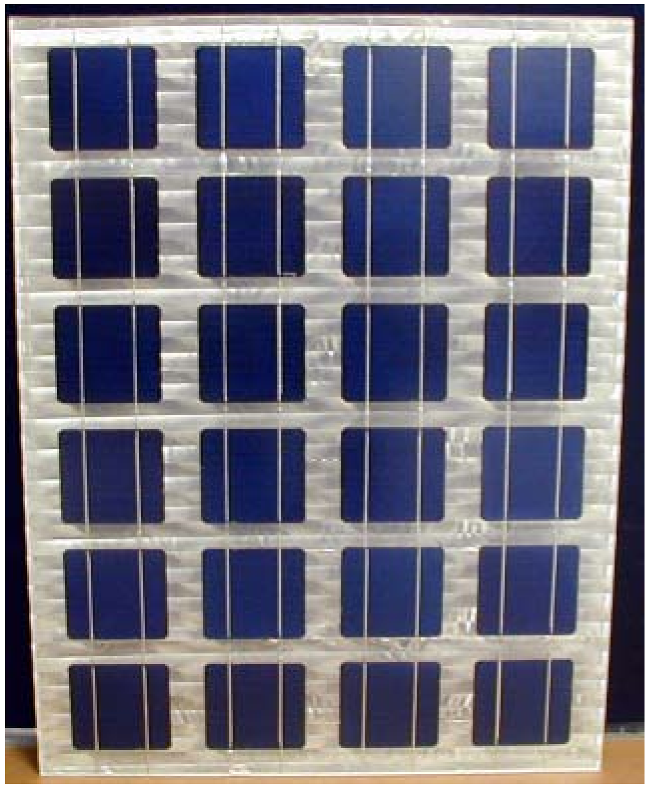


Figure 3. Reflector module incorporating design using 10 cm x 10 cm area cells.

in framing. A frameless module has the potential for delamination at the module edges under the action of this mismatch stress if the glass/encapsulant bonding strength were to be reduced by any means, e.g., by defective manufacturing processes (poor priming), or environmental degradation in the field (moisture). For this reason, it will be recommended that this construction should be used only in the framed configuration. We plan to continue our work in Phase III to model other encapsulant/backskin material systems which have the potential for reduced interface stress.

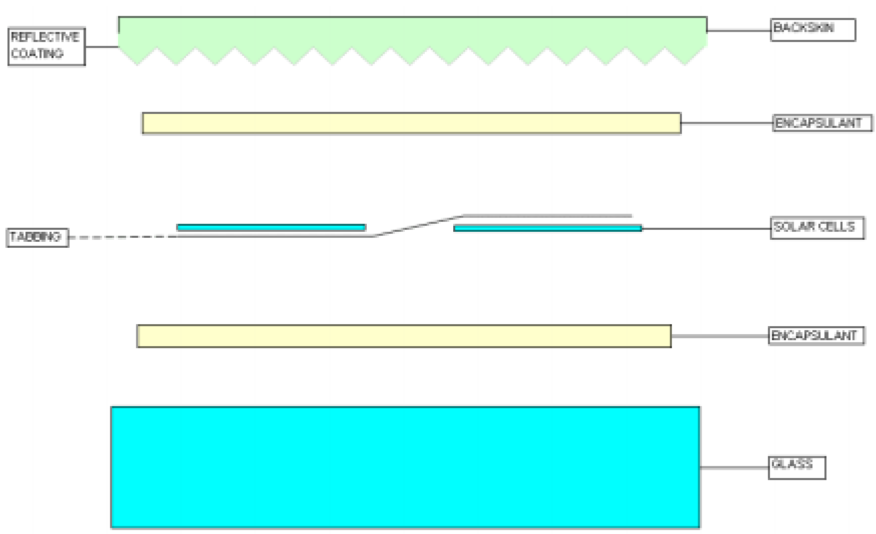


Figure 4. Schematic of reflector module laminate layout (Manufacturing schematic: layers in Figure 3 correlate from *bottom to top* above.)

Design studies for module sizes up to 300 W were completed in Phase II. Figure 3 above shows a design for a 150 W reflector module with 5 cm x 10 cm cell sizes as an example, with the laminate layers as illustrated in Fig. 4. This module is predicted to produce about a 50% enhancement in current. A summary of the reflector module design parameters for our 300 W module study is given in Table 6 below.

Table 6. Optimal cell size study for 300 W reflector module.

CELL SIZE	TOTAL CELLS	ENHANCEMENT	Voc(V)	Voc(V)*	Jsc(A)	Jsc(A)*	FF(%)	PP(W)
50 mm^2	266	40%	75.28	76.78	1.5	2.10	0.72	232
		50%				2.25		249
		60%				2.40		265
		70%				2.55		282
100 mm^2	168	35%	47.54	48.49	3.0	4.05	0.73	287
		40%				4.20		297
		50%				4.50		319
		60%				4.80		340
		70%				5.10		361

Assumptions:

1) 14% Cells
2) 27-mm spacing
3) Superstrate is 1/4" thick glass
4) Module dimension is 1854 mm x 1575 mm(73 inch x 64 inch)

Additional proposed work scope for Phase II in this task included development of manufacturing methods for the reflector module and a concept for a manufacturing floor equipment for reflector module manufacture. These milestones were completed and not influenced by the reliability issue of module construction. On account of the failure to qualify the reflector materials and demonstrate reliability, we reformulated the work scope in this task late in Phase II. The R&D work on a pilot reflector manufacturing line has now been postponed beyond the projected end of this subcontract. The replacement work in Q4 of Task 7 and years 3 Task 11 will investigate alternative construction materials and module designs for the reflector module, and the objective will be to demonstrate a new design and new materials which will pass all reliability testing. The new scope of work will focus on a number of reliability and material compatibility issues associated with encapsulant and backskin materials which now have become a critical impediment to further continuation of reflector module manufacture. The new work will encompass three areas: 1) study of chemical effects at encapsulant-glass interfaces to understand factors promoting adhesion and preventing delamination and differences between the standard EVA/glass system and our proprietary encapsulant/glass interfaces; (2.) evaluation of edge seals, backskin materials and encapsulants for different reflector/backskin/encapsulant combinations, including EVA, which will inhibit delamination factors and increase module lifetime and reliability; and (3.) investigation of chemical modifications and substitutions to reflector and backskin materials to reduce stresses resulting in delamination.

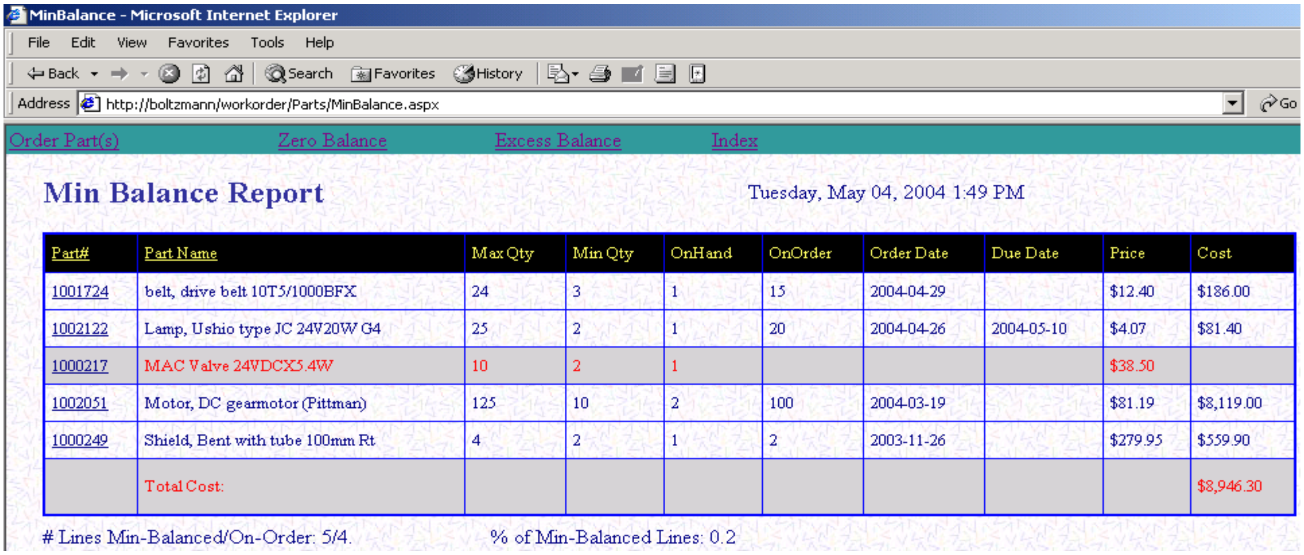
2.4 Task 8. Intelligent Processing

In this task, RSSI is planning to automate manufacturing diagnostic tools and Statistical Process Control (SPC) techniques currently under development. The automated SPC techniques will be applicable to future high throughput material handling lines planned for future generations with a cycle time of up to 1 per second for wafers and cells. The overall objective in this task is to develop a data and information-gathering network capable of accessing the sensors and diagnostic equipment developed in Task 5, along with accessing data already collected by individual equipment programmable logic controller (PLC) functions.

In order to reduce the overall manufacturing cost and improve operation efficiency, we have developed a Computer Maintenance Management System (CMMS) at RSSI. In Phase I, we completed installation of the CMMS control and monitoring networks. The details of the CMMS system architecture have been described in the previous report [1]. During that time, we completed prototyping and implemented the system primarily in the laser cutting area. Significant progress has been made since then and new capabilities have been added. In Phase II, we completed deployment of the CMMS in all three manufacturing areas in the Billerica plant – wafer production, cell line, and module manufacture. In addition, the system has been integrated into the company intranet and can be accessed from both the United States and our overseas locations.

The main segments of the CMMS system are: Repair Parts Inventory Management, Automated PM Scheduling, Equipment Downtime Tracking, Wireless Access and Utility Monitoring and Control. We describe next the work done in Phase II in the first three of these areas in implementing these capabilities in our manufacturing line in Billerica.

Repair Parts Inventory Management System. A machine repair parts inventory management system module has been added to the CMMS. This system module consists of: a barcode labeling system; a wireless inventory auditing capability with a handheld PC or PDA; and the software modules for ordering, receiving, and tracking machine parts. Figure 5 demonstrates a minimum balance report off the machine parts inventory system. It shows records of machine parts that have quantities on-hand below certain specified threshold (minimum) values. The system alarms users by highlighting the row of the machine part in red if an order has not been placed for that part. Other screens call up part orders placed between two given dates, listing purchase order numbers, order dates, vendor information, and order status. Clicking on the PO number links to the details page of that particular order. Also listed on the screen is information on the number and percentage of the orders that were placed as emergency. Emergency orders may require added cost or cause extended equipment downtime. An automated monitoring capability embedded in the inventory management system enables the system to alarm users by highlighting the row of the machine part in red if an order has not been placed for that part. Other screens call up part orders placed between two given dates, listing purchase order numbers, order dates, vendor information, and order status. Clicking on the PO number links to the details page of that particular order. Also listed on the screen is information on the number and percentage of



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Order Part(s) Zero Balance Excess Balance Index

Min Balance Report

Tuesday, May 04, 2004 1:49 PM

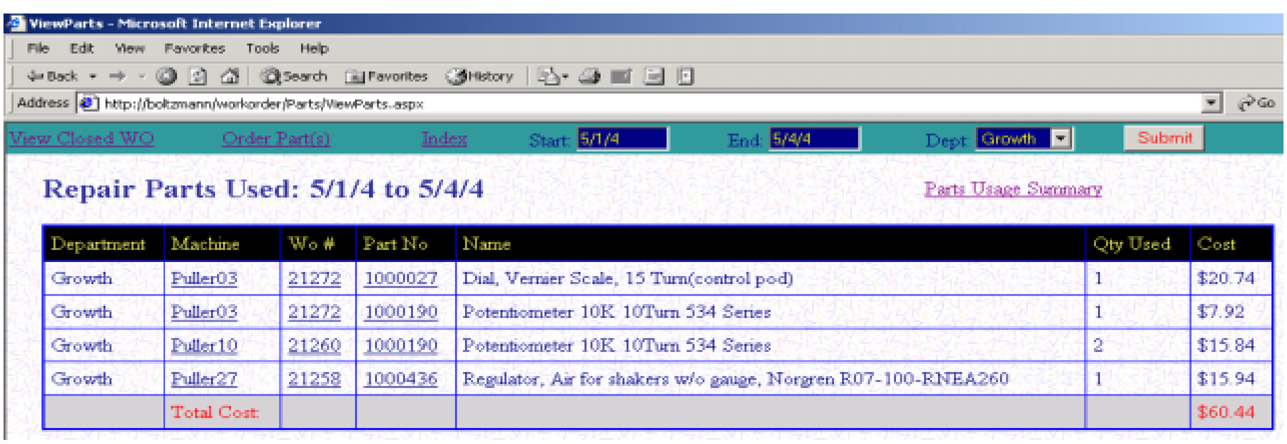
Part#	Part Name	Max Qty	Min Qty	OnHand	OnOrder	Order Date	Due Date	Price	Cost
1001724	belt, drive belt 10T5/1000BFX	24	3	1	15	2004-04-29		$12.40	$186.00
1002122	Lamp, Ushio type JC 24V20W G4	25	2	1	20	2004-04-26	2004-05-10	$4.07	$81.40
1000217	MAC Valve 24VDCX5.4W	10	2	1				$38.50	
1002051	Motor, DC gearmotor (Pittman)	125	10	2	100	2004-03-19		$81.19	$8,119.00
1000249	Shield, Bent with tube 100mm Rt	4	2	1	2	2003-11-26		$279.95	$559.90
	Total Cost:								$8,946.30

Lines Min-Balanced/On-Order: 5/4. % of Min-Balanced Lines: 0.2

Figure 5. Parts Minimum Balance Report with highlighted row(s) for reordering.

the orders that were placed as emergency. Figure 6 shows an example of repair parts used for a given time interval in the Crystal Growth department. Clicking on a work order number will bring you to a particular work order details page, while clicking on a machine name, e.g. "Puller 10" will link to the detailed usage of parts for that particular machine.

Automated PM Scheduling. An Automated Preventative Maintenance (PM) Scheduling module has been developed and added to the CMMS. The Automated PM Scheduling system consists primarily of a PM Tasks table, a PM Schedule table, and a series of class libraries codes and SQL* stored procedures. (*SQL as used here is a Microsoft database language which currently has no definition but originated elsewhere as 'structured query language'.) Users first create and enter the PM tasks to the task table for each machine category, e.g., growth pullers, laser cutters, or cell testers, etc. A step-by-step procedure instruction is also created for each PM task. The PM task defines the frequency of the scheduling for each machine category, and the type of PM to be performed by E/M technicians or production operators. After a PM task has been entered into the system, a new PM schedule can be created for an individual machine by entering the PM



ViewParts - Microsoft Internet Explorer

Address http://boltzmann/workorder/Parts/ViewParts.aspx

View Closed WO Order Part(s) Index Start: 5/1/4 End: 5/4/4 Dept: Growth Submit

Repair Parts Used: 5/1/4 to 5/4/4

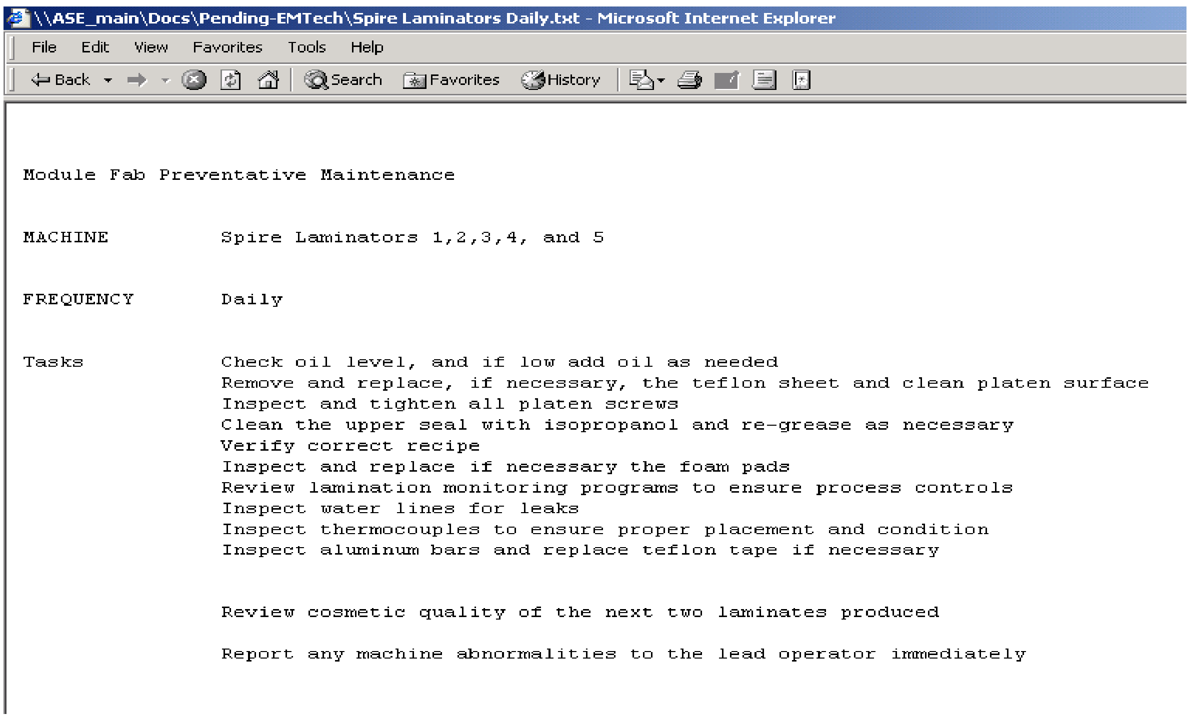
Parts Usage Summary

Department	Machine	Wo #	Part No	Name	Qty Used	Cost
Growth	Puller03	21272	1000027	Dial, Vernier Scale, 15 Turn(control pod)	1	$20.74
Growth	Puller03	21272	1000190	Potentiometer 10K 10Turn 534 Series	1	$7.92
Growth	Puller10	21260	1000190	Potentiometer 10K 10Turn 534 Series	2	$15.84
Growth	Puller27	21258	1000436	Regulator, Air for shakers w/o gauge, Norgren R07-100-RNEA260	1	$15.94
	Total Cost:					$60.44

Figure 6. Example of a screen showing Repair Parts Used between 5/1 – 5/4 in the Crystal Growth Department

Task ID, the machine ID, and the time when the first PM task is to be performed. A PM scheduling screen with this information tabulated for any time period can be called up by the user. The table in the screen updates each time it is open. Overdue PM schedules are highlighted in red. Clicking on any entry on the Task ID column brings up the individual PM task information page, which then links to a step-by-step instruction page for that particular PM task.

After a PM task is complete the actual time worked on the PM task by a technician or an operator is entered to the system. The system then automatically generates the next PM schedule for the same task on that machine based on the frequency of the given PM task. The system also allows for rescheduling of any PM task that has been entered for any given machine. It also provides reports to summarize PM history for a given machine in any time period. An example of a detailed laminator PM screen is shown in Fig. 7 below.



Module Fab Preventative Maintenance

MACHINE Spire Laminators 1,2,3,4, and 5

FREQUENCY Daily

Tasks
Check oil level, and if low add oil as needed
Remove and replace, if necessary, the teflon sheet and clean platen surface
Inspect and tighten all platen screws
Clean the upper seal with isopropanol and re-grease as necessary
Verify correct recipe
Inspect and replace if necessary the foam pads
Review lamination monitoring programs to ensure process controls
Inspect water lines for leaks
Inspect thermocouples to ensure proper placement and condition
Inspect aluminum bars and replace teflon tape if necessary

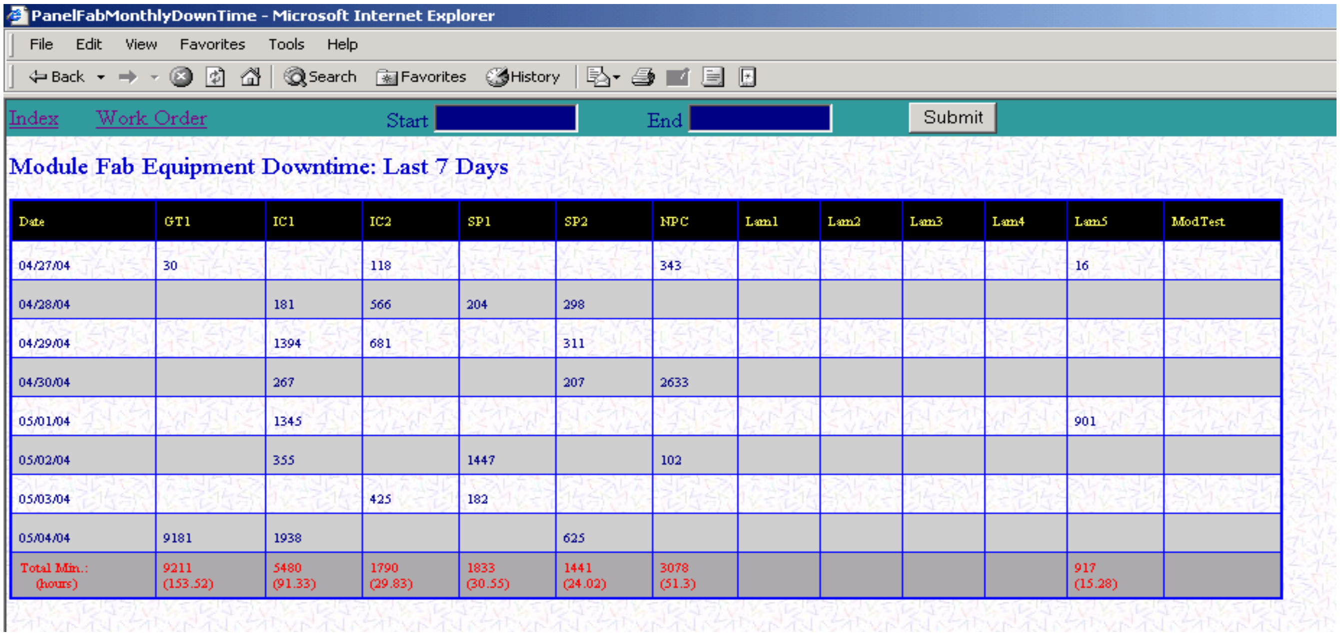
Review cosmetic quality of the next two laminates produced

Report any machine abnormalities to the lead operator immediately

Figure 7. Detailed procedure for daily preventative maintenance schedule for laminator.

Equipment Downtime Tracking. A new equipment downtime tracking system has been added to the CMMS, which updates and replaces an earlier version of the system. The previous system had relied on a timer variable in a PLC. However, the PLC on a machine has to be running in order to track the machine downtime. When a machine is powered down or its PLC is switched to debugging or programming mode, the downtime timer stops or resets. For this reason, the values reported by the earlier version of this system were often significantly different from the actual downtime.

To improve upon this, the new equipment downtime tracking system derives it time from the existing Work Order system that has been built as part of the CMMS. Since the Work Order system does not depend on any individual machines, the reported downtime values are more neutral and closer to true values. Figure 8 is an example of a daily Module equipment downtime report. This new system has been implemented in all production areas.



Module Fab Equipment Downtime: Last 7 Days

Date	GT1	IC1	IC2	SP1	SP2	NPC	Lam1	Lam2	Lam3	Lam4	Lam5	ModTest
04/27/04	30		118			343					16	
04/28/04		181	566	204	298							
04/29/04		1394	681		311							
04/30/04		267			207	2633						
05/01/04		1345									901	
05/02/04		355		1447		102						
05/03/04			425	182								
05/04/04	9181	1938			625							
Total Min.: (hours)	9211 (153.52)	5480 (91.33)	1790 (29.83)	1833 (30.55)	1441 (24.02)	3078 (51.3)					917 (15.28)	

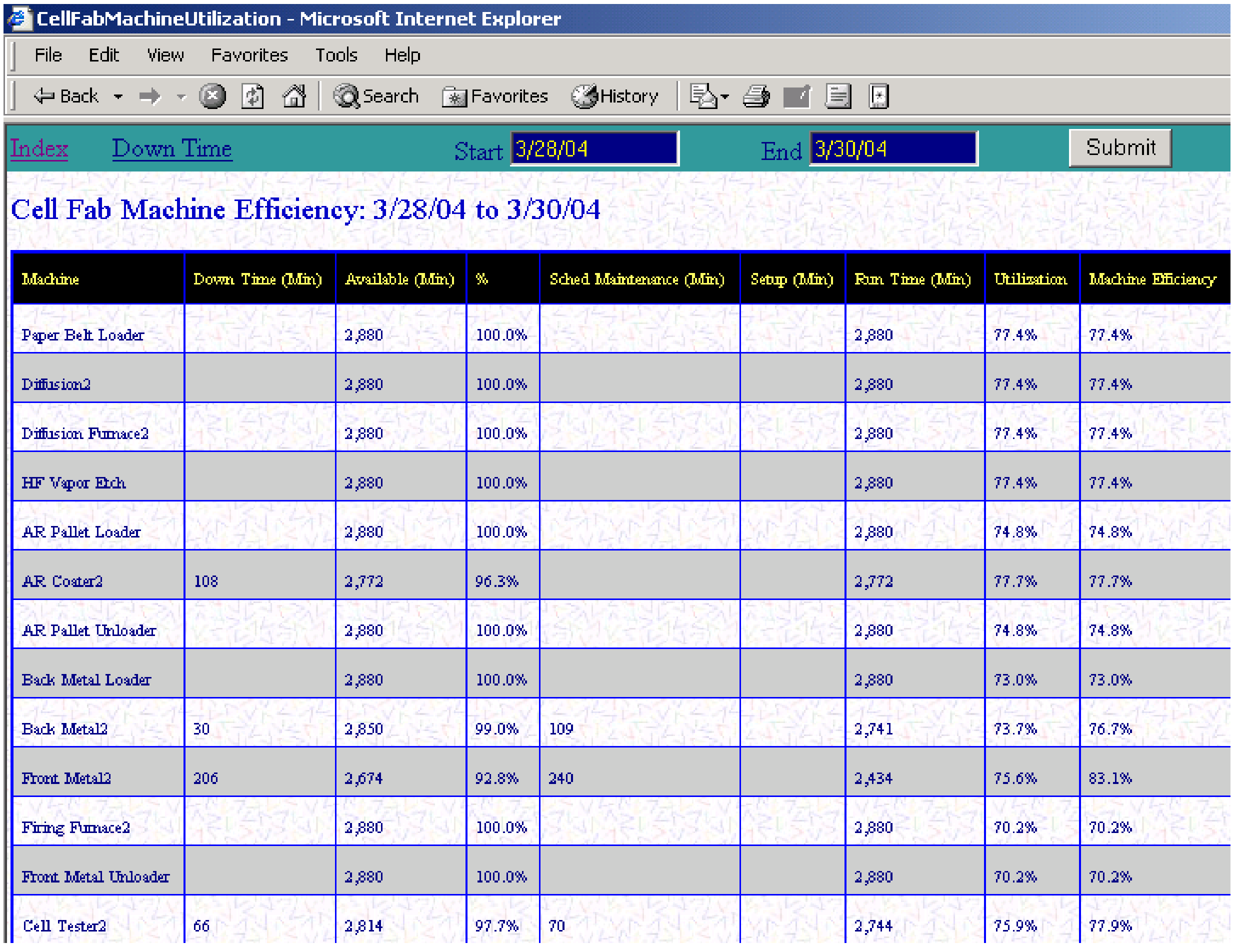
Figure 8. An example of daily equipment downtime report for module manufacturing line.

In addition to downtime the performance of a machine is measured through a new parameter called machine efficiency. The machine efficiency for any given time period is defined as a ratio of the actual number of parts produced divided by the capacity of the machine (Parts/Min.) times machine runtime, where the machine runtime is the total time available minus the time for scheduled PM and the machine setup. Figure 9 shows an example of machine efficiency for the new cell line equipments in a given time period.

3. Summary and Plans for Phase III

R&D has been carried out on manufacturing technology on diagnostic equipment and information systems for high throughput wafer, solar cell and module lines configured for EFG wafers. EFG wafer production in Billerica currently is at a 20 MW level. A 12 MW cell line was installed in Billerica during the Phase II program. The interconnect and module areas will be automated and equipment upgraded in 2004/5 to increase throughput to match the cell line.

The new manufacturing technology put in place and being planned for Billerica for the future requires diagnostic and data management in order to streamline operations, improve performance in yield and throughput, and reduce variable manufacturing costs. In Task 5 on in-line diagnostics, we have developed process control software and installed it on crystal growth furnaces for monitoring certain growth variables, e.g., for measuring on a continuous basis parameters such as temperature and buckle/amplitude. A method suitable for measuring thickness on-line during tube growth simultaneously on all faces of the octagon has been demonstrated, and equipment will be purchased and installed for optimization and integration into control algorithms. A crack detection method was



Machine	Down Time (Min)	Available (Min)	%	Sched Maintenance (Min)	Setup (Min)	Run Time (Min)	Utilization	Machine Efficiency
Paper Belt Loader		2,880	100.0%			2,880	77.4%	77.4%
Diffusion2		2,880	100.0%			2,880	77.4%	77.4%
Diffusion Furnace2		2,880	100.0%			2,880	77.4%	77.4%
HF Vapor Etch		2,880	100.0%			2,880	77.4%	77.4%
AR Pallet Loader		2,880	100.0%			2,880	74.8%	74.8%
AR Coater2	108	2,772	96.3%			2,772	77.7%	77.7%
AR Pallet Unloader		2,880	100.0%			2,880	74.8%	74.8%
Back Metal Loader		2,880	100.0%			2,880	73.0%	73.0%
Back Metal2	30	2,850	99.0%	109		2,741	73.7%	76.7%
Front Metal2	206	2,674	92.8%	240		2,434	75.6%	83.1%
Firing Furnace2		2,880	100.0%			2,880	70.2%	70.2%
Front Metal Unloader		2,880	100.0%			2,880	70.2%	70.2%
Cell Tester2	66	2,814	97.7%	70		2,744	75.9%	77.9%

Figure 9. A snapshot showing machine efficiency in cell line.

evaluated, but found to be lacking in being able to consistently discriminate cracks of all lengths in wafers; more work will be done in Phase III to improve it.

Other work in Task 5 has developed and evaluated diagnostic methods for solar cell manufacturing. Although initially we concentrated on diagnostics improvements in measurements of bulk resistivity and wafer electronic quality (via Photoluminescence), during Phase II, we expanded our original list of diagnostic requirements for the new cell line (Table 3 above) for future study in Phase III. During Phase III we also plan to increase throughput from 1200 to 1500 parts per hour.

In Task 6 during Phase II, we worked on improving yield and throughput of the 12.5 cm wafer production system (crystal growth, lasers and etching) first demonstrated in Phase I. Equipment performance for growth of wider face (12.5 cm vs the standard 10 cm EFG tube) and larger diameter octagons (38 cm vs the standard 30 cm) was explored in order to improve productivity. This development was aided with magnetic and thermal computer models developed at Stony Brook University. The increase in face width results in higher stresses acting on the tube during growth, and this requires development of lower stress furnace configurations. A significant part of the ongoing R&D is on application of diagnostics during growth to monitor flatness, thickness, temperature profiles (both experimental and thermal models) and residual stress. The work in Phase III will expand to include automation of a number of aspects of the EFG crystal growth process, and complete implementation of diagnostic techniques.

In other work in Task 6, improved laser cutting has been demonstrated with the trial of a higher speed laser in manufacturing. The new laser is capable of cutting with a speed about 60% higher than the lasers being used in current production. It also produces reduced damage and allows reduction of post-cutting etching by about 10%. With additional improvements coming from better diagnostics of cutting station performance provided by our CMMS data collection network, we have achieved over a 20% improvement in the output of a single laser cutting station under manufacturing conditions. A concept for outfitting two such lasers on one cutting station has been explored, but it has not been found to be cost effective for retrofitting existing production technology in Billerica at the present time. This scenario will be reexamined near the end of Phase III of the program to determine if sufficient justification exists then for going forward with this concept.

We developed and constructed a number of prototype reflector materials in Phase II work in Task 7, but found that the prototypes failed in important aspects of reliability testing. It was therefore not possible to complete milestones on pilot plant demonstration for reflector manufacture. In Phase III, emphasis will be placed on searching for new materials to overcome these reliability issues.

A central focus of Task 8 has been the development of a company wide data retrieval and process monitoring computer system. We have configured our data retrieval system around a central dedicated server and a Computer Maintenance Management System (CMMS) was developed to use for setting up equipment downtime tracking, training and preventative maintenance functions in the crystal growth and laser cutting areas. These capabilities were expanded to our new cell and module lines in Phase II. In Phase III, we plan to carry out R&D on the manufacturing lines to further optimize and integrate the data collection and CMMS systems into our operations and use them to improve yield and throughput throughout manufacturing to meet program goals.

Acknowledgments

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[1] Phase I Annual Report, “EFG Technology and Diagnostic R&D for Large-Scale PV Manufacturing”, DOE/NREL Subcontract No. ZDO-3-30628-13.

[2] J. Kalejs et al., “Advances in High Throughput Wafer and Solar Cell Technology for EFG Ribbon”, in: *Proc. 29th IEEE PVSC (2002)*, p. 74.

[3] C. K. Bhihe et al., “Residual Stresses in Crystal Growth“, *J. Crystal Growth* **137** (1994), p. 86.

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14. ABSTRACT *(Maximum 200 Words)*

The objective of this subcontract over its duration was to carry out R&D to advance RWE Schott Solar Inc. (formerly ASE Americas) – "RSSI" — manufacturing technology, processes and capabilities of wafer, cell, and module manufacturing lines, which will help configure them for scaling up of EFG ribbon technology to the 50-100 MW PV factory level. The basic EFG technology principles have already been established and are being demonstrated on the scale of 10-20 MW manufacturing lines. By the successful completion of this effort, RSSI is planning to reduce overhead costs of production and of direct, variable manufacturing costs with the scale up of EFG processes and equipment currently in use. To achieve these objectives, RSSI needs to maintain or enhance yield, quality, process control, and throughput relative to present levels throughout the three areas of wafer, cell, and module manufacture.

15. SUBJECT TERMS

PV; module; solar cells; manufacturer; crystal growth; temperature fields; crystal (tube) thickness; crack detection; cell line diagnostics; photoluminescence;

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